AD-A277 552

March 21, 1994 | Reprint

The Ground-level Enhancements of 1989 September 29 and October 22

PE 61102F
PR 2311
TA G4
WU 02

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PL-TR-94-2059

94-09616

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14. SUBJECT TERMS

Solar protons, Ground level events, Solar-terrestrial phenomena, Cosmic rays, Asymptotic directions, Geomagnetic field, Magnetosphere

15. NUMBER OF PAGES: 7

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

The Ground-level Enhancements of 1989 September 29 and October 22

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1. Introduction

Cosmic rays are fully ionised nuclei of very high energy (10^9–10^{20} eV) which bombard the earth almost isotropically. They have an abundance distribution similar to neutral matter in the galaxy (~90% protons) and are principally of non-solar system origin. The energy spectrum follows a power law of slope −2.6 and the acceleration mechanisms by which the particles gain their energy are poorly understood, particularly at the very highest energies.

On rare occasions a solar flare will accelerate protons to sufficiently high energies for these particles to propagate along the heliomagnetic field to the earth and be detected as a sharp increase in the counting rate of ground based cosmic ray detectors. Such events are known as Ground Level Enhancements (GLEs) and there have been 53 recorded since reliable records began in the 1940s.

The largest GLE ever recorded was on 1956 February 23 and reached a peak 45 times the usual cosmic ray background level. Typical GLE peak levels range from ~5–40% above background with very few exceeding 100%.

There were 13 GLEs in the period 1989 July–1991 July corresponding to the most recent maximum in the solar sunspot cycle. Such a high frequency of events is unprecedented.

In this paper we model the arrival of solar accelerated particles at the earth and their detection by ground based systems. We consider two events, namely those of 1989 September 29 and October 22, taking into account disturbed geomagnetic conditions.

2. Particle Propagation to Earth

Solar flares and other magnetic phenomena at the sun may give rise to GLEs. The acceleration of charged particles to energies sufficiently high to be detected by ground based cosmic ray detectors is poorly understood and several mechanisms have been proposed and are hotly debated.

Propagation of these particles to the earth is more readily explained. The solar magnetic field is 'frozen' into the solar wind plasma which flows radially outward from the sun. Coupled with the 27-day rotation of the sun, the field near the solar equator forms an Archimedean spiral structure and a field line connecting the earth to the sun typically emanates from the sun at a longitude ~ 60°W of the earth-sun line (footpoint) and intersects the earth at ~ 45° as shown in Figure 1. This field line, linking the sun to the earth, is referred to as the 'garden hose' field line.

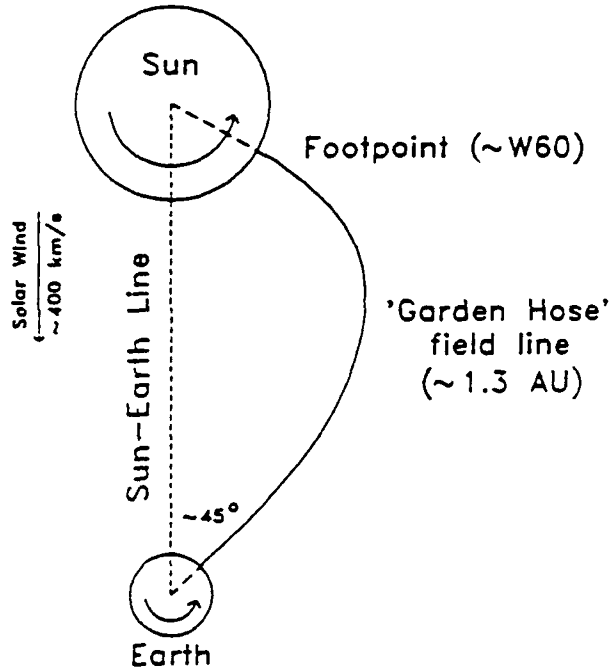

Figure 1: Schematic representation of the 'garden hose' field line connecting the sun and earth.

Charged particles gyrate around magnetic field lines as they propagate along them. Therefore, particles accelerated at the sun near to the footpoint of the garden hose field line will propagate easily to the earth. Particles accelerated some distance from the footpoint must cross field lines before they can propagate to the earth along the garden hose.

The direction of the garden hose field line at the earth and its footpoint at the sun vary considerably, both being strongly dependent on interplanetary conditions. In particular, variations in the solar wind speed and disturbance of the field by shocks will have significant effects on the large scale field structure. There is, however, a strong tendency for the solar active region responsible for a GLE to be located at westward solar longitudes (Bendoricchio 1991).

Of the seven GLEs clearly attributed to an eastern source longitude only three were farther east than 15°.

3. Effect of the Earth's Magnetic Field

On reaching the earth particles encounter the geomagnetic field. In traversing the field the particles undergo a rigidity (momentum per unit charge) dependent deflection of their trajectories. As a result it is necessary to model the 'viewing cones' of cosmic ray neutron monitors. Using models of the geomagnetic field we calculate the particle arrival directions, outside the magnetic field, that have access to the monitor field of view . In the past this has only been possible for undisturbed geomagnetic field models. Recent improvements in understanding of the structure of the disturbed geomagnetic field have allowed us to take into account these deformations and dramatically improve the accuracy of the viewing cone calculations (Kobel 1989). This is important because the presence of a GLE invariably means that the sun is in an active state and, as a result, the influence of the solar wind and shocks are likely to have caused magnetically disturbed conditions at the earth.

A second aspect of the particle trajectory deflection is that the minimum rigidity a particle must have to gain access to a ground based neutron monitor depends on the location of that monitor on the earth's surface. This minimum rigidity is termed the 'cut-off' for the site and can be as high as 15 GV for equatorial observatories. At mid-latitudes the cut-off reduces to a few GV and at polar sites to

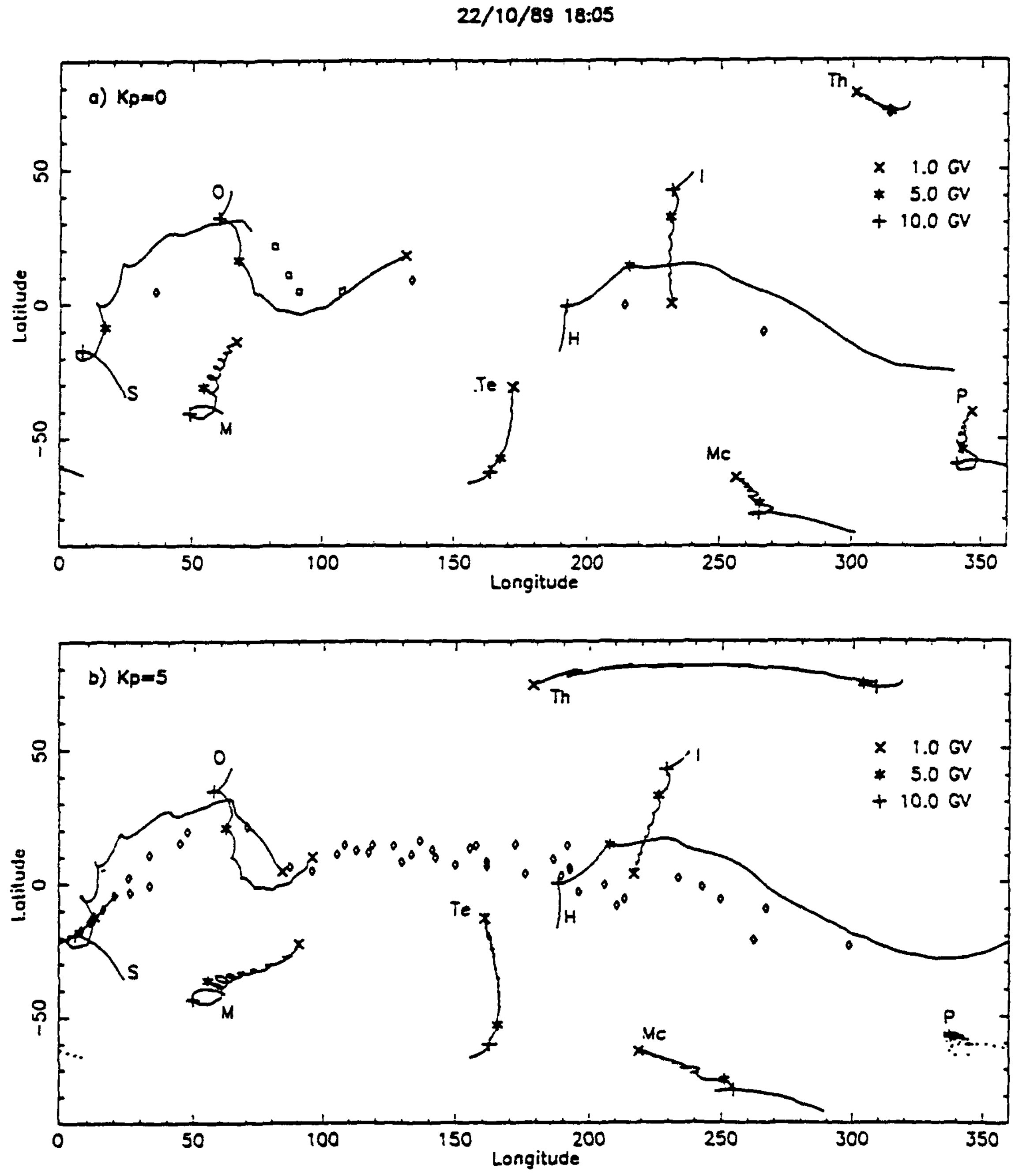

Figure 2: Neutron monitor asymptotic cones of view for 18:05 UT 1989 October 22 for (a) quiet geomagnetic conditions and (b) disturbed geomagnetic conditions. Sanae S and □ : Oulu O and △ : Hobart H and ◇ : Mawson M; Terre Adelie Te; Thule Th; Inuvik I; McMurdo Mc; South Pole P. The viewing directions at 1, 5 and 10 GV are indicated by x, * and + respectively.

virtually zero. Additionally, the particles lose energy in penetrating the atmosphere so that the minimum proton energy which gives rise to a response at sea level amounts to ~0.5 GeV, equivalent to a rigidity of about 1 GV. In Figure 2 the viewing cones of a sample of neutron monitors are shown for a) quiet geomagnetic conditions (Kp = 0) and b) disturbed geomagnetic conditions applicable at the time of the 1989 October 22 GLE (Kp = 5). It is clear that significant changes in neutron monitor viewing cones occur with a disturbed field, particularly for low cut-off polar stations. See Kobel (1989), Flückiger and Kobel (1990), Flückiger et al. (1990) and Bieber et al. (1992) for further discussion.

The observations of GLEs at multiple sites, with varying cut-offs, allows the determination of the direction of arrival of the particles, the distribution about this arrival direction or anisotropy and the spectrum of the event. Furthermore, the absence of a response to a GLE at higher cut-off rigidity observatories gives an estimate of the maximum particle rigidities involved in the event.

4. Modelling GLEs

Techniques for modelling the dynamic behaviour of GLEs throughout their development are not presently available. It is possible, however, to analyse the particle flux and distribution on an instantaneous basis, following a standard technique (Shea and Smart 1982; Humble et al. 1991a; Humble et al. 1991b). The responses of numerous neutron monitors world-wide are modelled to determine a best fit spectrum and spatial distribution of the particles arriving from the sun. The model for the neutron monitor response is of the form

$$I = \sum_{P_c}^{\infty} J_a \; (a,P) \; S(P) \; G(a) \; \delta P$$

where I is the recorded percentage increase at the time
P is the particle momentum (in GV)
P_c is the cut-off for that neutron monitor
a is the pitch angle of the particles
J_a is the interplanetary differential flux
S is the specific yield function of the neutron monitor
and G is the pitch angle distribution of the arriving particles.

The specific yield function includes two components, the neutron monitor yield function (Lockwood et al. 1974), which gives the response to particles arriving at the top of the atmosphere above the detector, and the cones of viewing described above.

5. 1989 September 29 GLE

The 1989 September 29 GLE was the first such event to be observed by all detectors in the present Australian neutron monitor network, which stretches from Mawson, Antarctica to Darwin in the tropics. To gain access to the Darwin neutron monitor the rigidity of the solar accelerated particles must have extended to at least 15 GV. Furthermore, surface muon detectors at Hobart and Mawson also observed the increase, confirming the high energy nature of the event. No increases were seen at either site by the underground telescopes. The 1956 February 23 GLE is the only previous report of muon detection of solar particles at both these observatories (Fenton et al. 1956).

Table 1 shows details of the Australian neutron monitors and the times of on-set and maximum response to the enhancement (corrected to the mean observatory pressure) while Figure 3 shows the time profile from these stations. Note that problems with the recording electronics at Brisbane required data recovery from a chart record.

Table 1: Australian Neutron Monitor Observations of 1989 September 29 GLE

Station	Cut-off GV	On-set UT	First Max UT	First Max %	Second Max UT	Second Max %
Mawson	0.20	11:54–55	not seen		13:25–30	230
Mt Wellington	1.80	11:46–47	12:25–30	342	13:15–10	344
Hobart	1.84	11:46–47	12:15–30	300	13:15–20	291
Brisbane	6.99	11:50–55	12:05–20	79	not seen	-
Darwin	14.09	11:50–55	11:55–15	13	not seen	

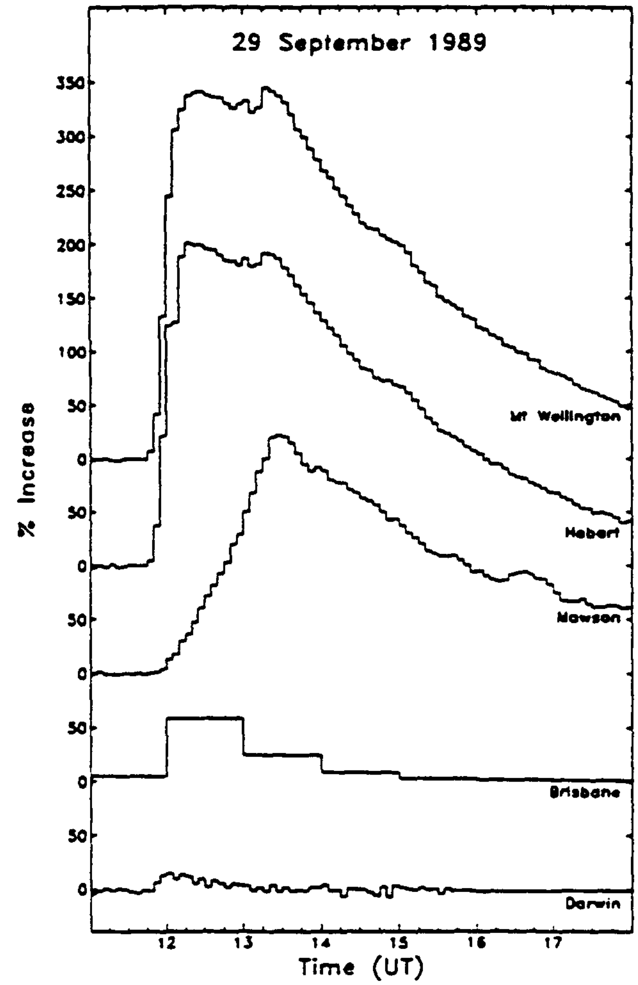

Figure 3: 1989 September 29 GLE as observed by the Australian neutron monitor network

Table 2 shows the hourly surface muon telescope responses, corrected to the mean observatory pressure, for the Hobart and Mawson observatories. Data on shorter time-scales are not available for these instruments.

Table 2: Mawson and Hobart Surface Muon Observations of 1989 September 29 GLE

Station	Zenith	Azimuth	Threshold GV	Increase % 12:00–13:00 UT	13:00–14:00 UT
Mawson	42°	N	~3	2.5	1.7
	42°	S	~3	2.5	1.7
	62°	N	~5	1.3	1.3
	62°	S	~5	1.5	1.3
Hobart	0°	V	~2.5	28.0	8.4

The solar region (NOAA region 5698) believed responsible for this event had rotated to ~15° behind the western limb of the sun (~105°W). The NOAA/GOES-7 spacecraft observed an X-ray event on-set at 10:47 UT which lasted 4 hours. The maximum intensity of X9.8 at 11:33 UT was accompanied by a loop prominence system seen in H_α and discrete frequency radio bursts. At 8800 MHz the commencement was at 11:20 UT and maximum at 11:37 UT.

It is clear from Figure 3 that the event has complex structures with two maxima, the first seen by all stations except Mawson and the second not seen by the low latitude stations Brisbane and Darwin. The event was analysed for the two maxima and during the decay phase.

The spectrum may be described in terms of the particle flux arriving within one steradian of the apparent source direction, $J_{\|}$, or as an average integrated over the full pitch angle distribution, J_{av}. The spectra are summarised in Table 3 and are quoted as power laws in the range 1 to 2 GV together with the rate of power law exponent steepening, $\delta\gamma$, above 2 GV. J is in units of $(cm^2\ s\ ster\ GV)^{-1}$. Source direction results from the modelling are also shown. The spectra and particle pitch angle distributions are shown in Figures 4 and 5.

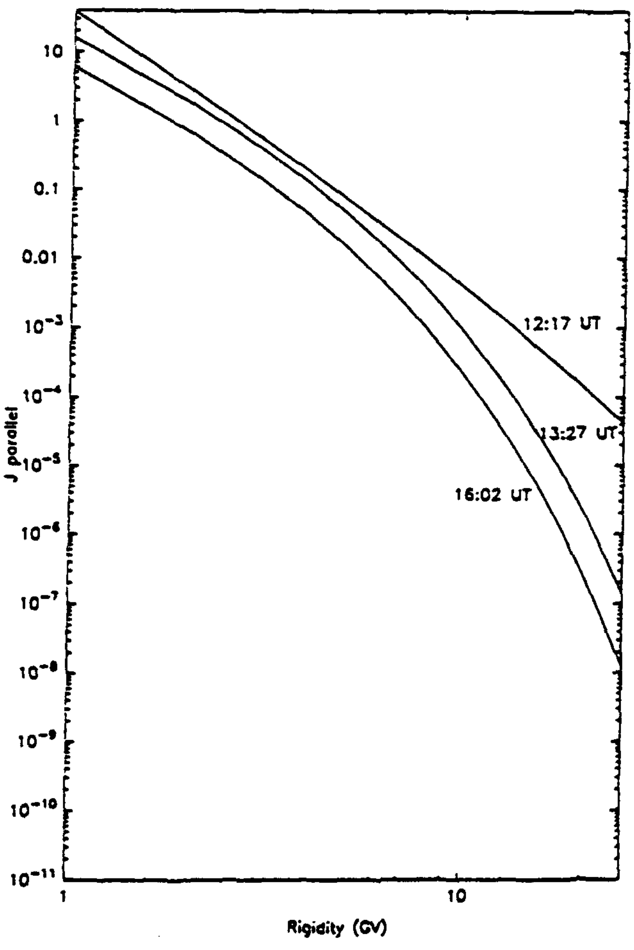

Figure 4: Derived spectra of the 1989 September 29 GLE

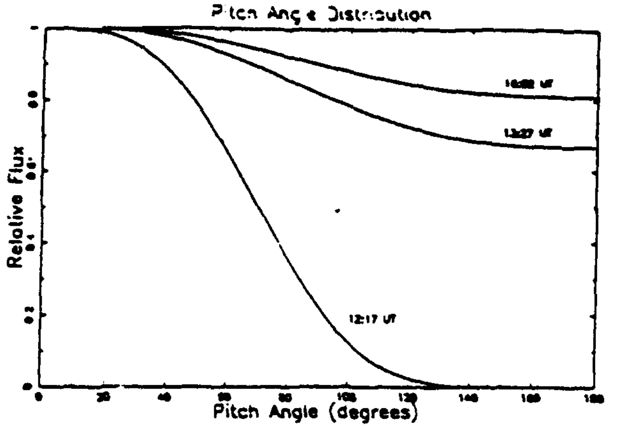

Figure 5: Derived particle pitch angle distribution of the 1989 September 29 GLE

Table 3: Derived Spectra and Apparent Source Direction for 1989 September 29 GLE

Time UT	$J_{\|}$	J_{av}	γ	$\delta\gamma$ per GV(>2 GV)	Source Lat	Source Lon
12:15–20	38.34	13.62	−3.75	−0.08	−4°	295°
13:25–30	15.96	13.08	−3.00	−0.43	−7°	280°
16:00–05	6.07	5.43	−3.00	−0.50	−10°	240°

The apparent 'source' direction was westward of the nominal 'garden hose' direction but we do not have knowledge of the actual interplanetary magnetic field (IMF) as IMP-8 was in the geomagnetic tail at the time. The free space source direction moved slightly southward during the enhancement. The longitude changes only reflect the earth's rotation. The event was also slightly anisotropic and showed significant reverse particle propagation. The spectral steepening, indicated by $\delta\gamma$, was notable later in the event (see Figure 4). Thus the spectrum was quite hard at the time of the first maximum and softened throughout the remainder of the event. The free space particle flux in the region of the earth also decreased.

The Mawson response to this event is due to particles propagating in the 'reverse' direction while the other stations observe 'forward' propagating particles. It is clear that the time of the first maximum is dominated by the higher rigidity particles while the lower rigidity flux reaches its maximum at the time of the second peak. In modelling the response at Darwin to the high energy maximum a significant fraction of the detected particles were found to have arrived from non-vertical directions. This is consistent with the large variation in geomagnetic cut-off between vertical and westward directions at Darwin. The derived source arrival direction is also in good agreement with the observation by Swinson and Shea (1990) of shallow underground muons at the Embudo observatory. This is the only GLE for which an underground detector has recorded a response, further demonstrating the intensity and spectral hardness of the event.

6. 1989 October 22 GLE

The GLE of 1989 October 22 was quite different in structure from the 1989 September 29 event just described. It was the second of three GLEs which have been associated with the same solar active region, namely NOAA/USAF Region 5747. A coincident X-ray event commenced at 17:08 UT, peaked at 17:57 UT (X2.9), lasted four hours and was accompanied by H_α emission. Radio emission at frequencies of 245–15400 MHz commenced at ~17:30 UT. This flare was located at S 27°, W 31° on the solar disk.

The GLE was observed at many stations in the world wide neutron monitor network but a 'precursor' peak was observed at only five stations (Bieber et al. 1990, Mathews and Venkatesan 1990). These observations are shown in Figure 6 and summarised in Table 4. Again, the data have been corrected to the mean observatory pressure.

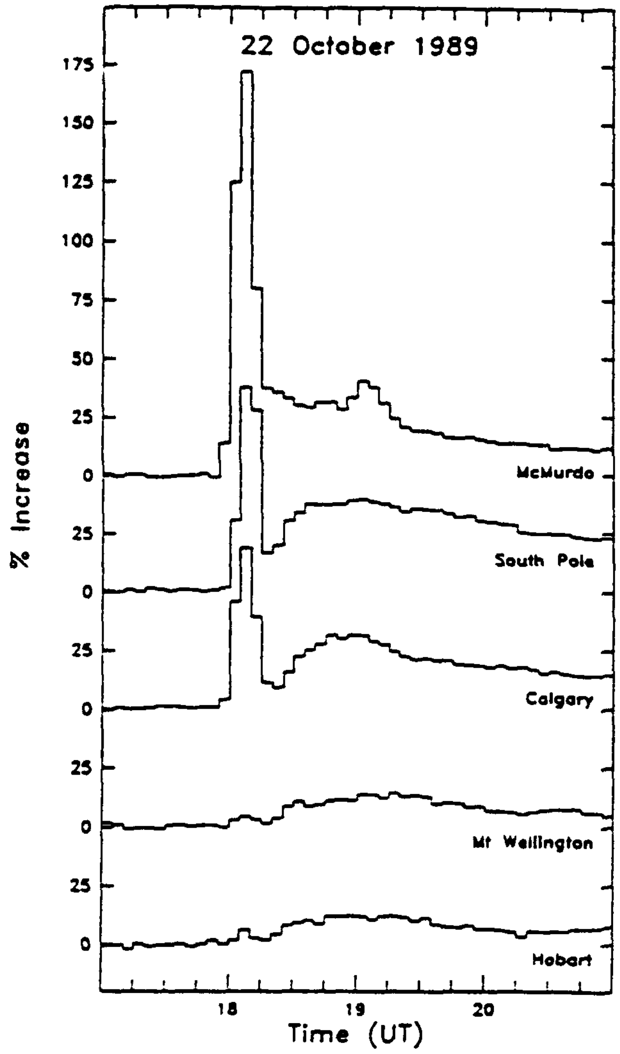

Figure 6: Observations of the 'precursor' to the 1989 October 22 GLE

Table 4: Neutron Monitor Observations of 1989 October 22 GLE Precursor at 18:05–10 UT

Station	Cut-off GV	Increase %
McMurdo	0.00	172
South Pole	0.02	88
Calgary	1.01	69
Hobart	1.69	6
Mt Wellington	1.69	5

The main GLE increase is shown in more detail in Figure 7 for many widely dispersed stations. It is clear that the event is quite complex with several significant peaks implying multiple particle injections or varying particle acceleration either at the solar source or in propagation to the earth.

The sharp 'precursor' event has been modelled as described earlier in this paper. Initial efforts to model the 'precursor' with an undisturbed geomagnetic field were unsuccessful and no satisfactory fit could be derived. The geomagnetic field was, however, highly disturbed at this time with Kp= 5+ (see Figure 2 described earlier).

Taking account of the disturbed geomagnetic conditions it was possible to obtain an excellent fit to the arriving par-

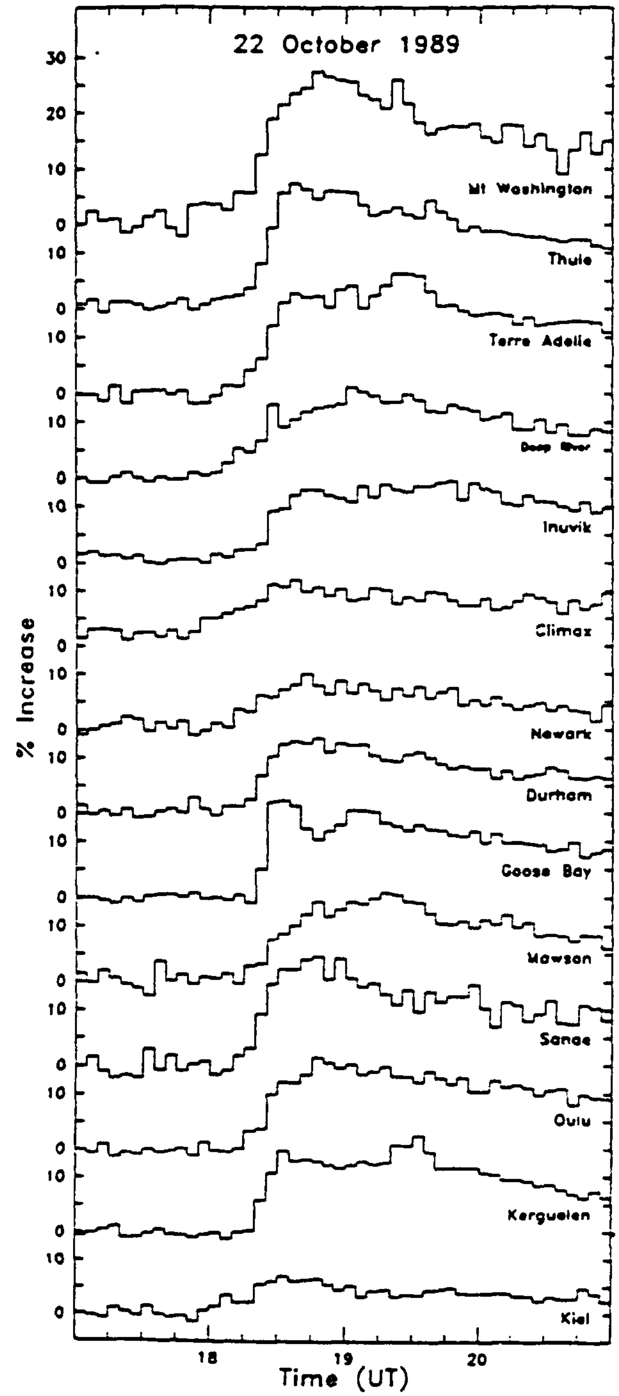

Figure 7: World-wide observations of the 1989 October 22 GLE

ticle distribution. The spectrum was best described by

$$J_{||} = 35.87\ P^{-5.0} \qquad \text{or} \qquad J_{av} = 3.69\ P^{-5.0}$$

with a constant spectral slope. The pitch angle distribution was found to be extremely anisotropic as shown in Figure 8. The apparent source arrival direction was −48°, 265°.

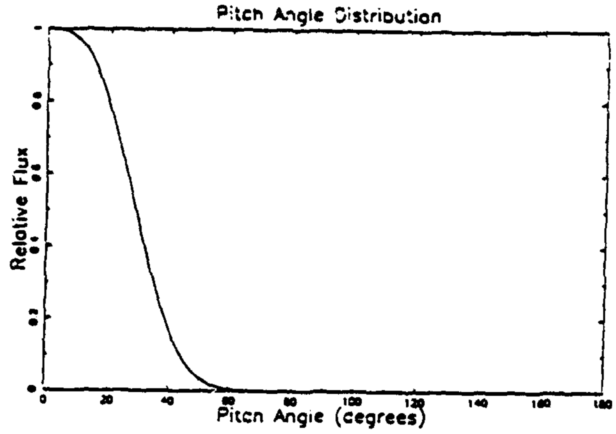

Figure 8: Derived particle pitch angle distrib ution of the 22 October 1989 GLE precursor.

This is the first time that it has been shown to be essential to include geomagnetic disturbance parameters in the GLE modelling to obtain satisfactory parameters for the event.

The cause of this very highly anisotropic 'precursor' is unclear. As no direct solar neutrons were observed at earth it is unlikely that the event was due to decaying of neutrons on the 'garden hose' field line with subsequent propagation to earth, as is proposed for the 1989 October 19 GLE precursor (Shea et al. 1991). No information on the interplanetary magnetic field is available for this event, again because IMP-8 was in the magnetotail, but the apparent source direction was very close to the sub-solar longitude of 271°. It is also well south of the sub-solar latitude of −11°. The source direction is thus a long way from the nominal 'garden hose' direction some 45° westward of the sub-solar point. Although we have no interplanetary field data for the event, it is known from IMP-8 measurements that a fast solar wind stream (>700 km s^{-1}) was present on October 20 and 21 and may well have continued until the time of the event. Such high speed streams tend to flatten the curve in the 'garden hose' field line and move the field line direction at earth closer to the sun-earth line. The IMF direction at earth recorded by IMP-8 on October 21 at 22:00 UT was −85° and varying considerably up to mid-latitudes. The last IMP-8 recording before entering the geomagnetic tail on October 22 was −42° at 02:00 UT. In light of the IMF structure one day prior to the GLE, the derived source direction is reasonable. It seems likely that the 'precursor' event involved an unusual particle injection/acceleration at the sun and further studies are continuing.

The main GLE was complex with several peaks. We have analysed the event at four times corresponding to the peaks and the decay phase. The derived spectra and apparent source directions at these times are shown in Table 5 together with the results of the precursor analysis. The spectra and derived pitch angle distributions are shown in Figures 9 and 10.

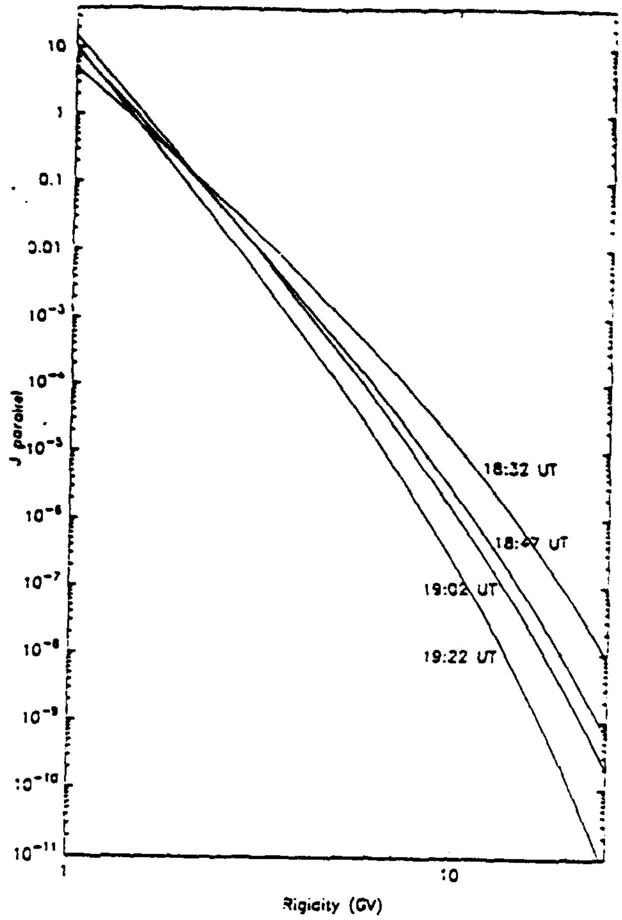

Figure 9: Derived spectra of the 1989 October 22 GLE

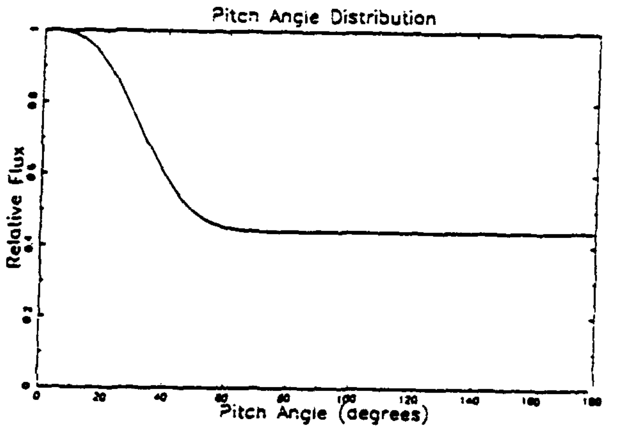

Figure 10: Typical derived particle pitch angle distribution of the 1989 October 22 GLE

Table 5: Derived Spectra and Apparent Source Direction for 1989 October 22 GLE

Time UT	$J_{\|\|}$	J_{av}	γ	$\delta\gamma$ per GV(>2 GV)	Source Lat	Source Lon
18:05–10	35.87	3.69	−5.0	0.0	−48°	265°
18:30–35	5.09	2.72	−5.0	−0.2	−62°	225°
18:40–45	9.35	5.20	−6.0	−0.2	−60°	220°
19:00–05	15.06	8.05	−6.5	−0.2	−64°	210°
19:20–25	10.22	5.91	−6.8	−0.3	−53°	182°

It is clear that the spectrum softened throughout the event and the pitch angle distribution showed mild anisotropy and reverse propagation which remained relatively constant. The apparent source longitude is very close to the garden-hose longitude but the latitude is even further southward than during the precursor. The source direction had moved back to mid-southern latitudes during the declining phase of the GLE.

The model fits to the GLE were quite acceptable but not as good as the excellent fits to the precursor or to the September 29 GLE. In part, this is probably due to the more complex structures present during this event.

To determine error estimates on all parameters it will be necessary to establish 95% confidence contours in parameter space. This is extremely computer intensive and work is continuing. We have estimated the errors as: spectral exponent $\pm$ 0.2; $\delta\gamma \pm 0.1$; source latitude $\pm 2°$; and source longitude $\pm$ 5°. These errors exclude possible systematic variations which may arise if a different yield function is employed.

We have compared our spectra to those reported by Bieber and Evenson (1991) and find that they are broadly consistent but with a tendency to be slightly softer. This may relate in part to different yield functions employed (necessary due to the different experimental technique) and is under continued investigation.

7. Conclusion

We have shown that extended particle pitch angle distributions were present during the GLEs studied in this paper. Solar accelerated protons should reach the earth travelling parallel to the IMF unless scattered nearby. This implies that, with the exception of the precursor, significant scattering regions were present within a few particle gyroradii of earth for both events.

The two GLEs highlighted in this paper indicate that present understanding of the acceleration and propagation of high energy particles is still in its infancy. Present theoretical models are too simplistic to account for the complex structures observed. The derivation of accurate descriptive parameters for the structure of GLE particle distributions give important insights into and set limits on particle acceleration mechanisms at the sun. It is clear from the present on-going study that disturbed geomagnetic conditions must be included in the analysis of GLEs and it is likely that many conclusions from earlier studies will need to be reconsidered. For those GLEs where disturbed geomagnetic conditions existed (the majority) re-analysis of the data should be undertaken in the manner described here. It is also important to consider the same effects in past and present studies of Forbush decreases. Conclusions about energetic particle (>1 GeV) acceleration, propagation in the interplanetary magnetic field and interaction with shocks may need to be modified following such re-analysis.

The significantly southern source direction derived for the October 22 precursor and GLE may be due to unusual IMF conditions and has implications for GLE propagation models.

Acknowledgements

The authors wish to acknowledge the release of data by a number of institutions prior to publication. This work was supported in part by Australian Research Council grants and JLC acknowledges receipt of an Australian Research Council Postgraduate Research Award. JWB and PE acknowledge support of NSF grants DPP-8818586 and ATM-9014806.

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